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LA-UR -78-1316

TITLE: DESIGNING PASSIVE SOLAR BUILDINGS TO REDUCE TEMPERATURE SWINGS

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SUBMITTED TO: Arizona State University, Tempe, AZ
Department of Architecture, May 5, 1978

MASTER

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Form No. 836
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1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

DESIGNING PASSIVE SOLAR BUILDINGS TO REDUCE TEMPERATURE SWINGS*

by

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ABSTRACT

Control of temperature swings is a major consideration in design of passive solar heated buildings--especially so as the designer seeks to achieve most of the building heat from the sun. Observations of temperature swings in several passive buildings are cited. Methods of temperature control are discussed, both by means of control intervention such as using of auxiliary backup heating, ventilation, blowers; and by means of building design. The design approach is preferred as the main course with the intervention techniques used for fine tuning.

INTRODUCTION

It has not been very long since people challenged the basic feasibility of passive solar heating. How could such simple concepts as direct gain, thermal storage wall, solar greenhouse, thermosiphon, or roof pond systems really compete with sophisticated hardware? These questions are not heard so often any more; the basic viability of passive solar heating in the U. S. is now becoming widely accepted. This has come about mostly because of the undeniable and demonstrable effectiveness of a growing number of passive buildings. The basic measure by which these buildings are judged is the fuel bill and these have been quite low.

We are now moving to the next question. This might be put as follows: "Surely these buildings must be uncomfortable. They must bake when there is a lot of sun and freeze when it gets cold. If the building itself is to store heat, then the temperature swings must be uncomfortably large." This criticism has a bit more bite to it. In fact, there are many passive solar buildings for which it is quite true.

Other questions arise. Many who are quite knowledgable about solar heating will still ask, "What happens when there is a week of no sun"? They only need be reminded that an active system falters under such conditions also. Each needs auxiliary backup heat or the temperature may fall to uncomfortably low levels.

Many of the first generation of passive advocates would rather put on sweaters than pay their dues the utility company. This tough-it-out philosophy has not benefited the image of passive solar heating. To adopt such an attitude is short-sighted. Now, as always, a major function of the built environment is to provide good thermal comfort conditions within. It will be an error to promote passive solar heating and a change of life style at the same time.

If backup auxiliary heat can solve the problem of temperature minimums in the building, can it help reduce the daily temperature swings? Are these a real problem, or are they easily alleviated? The evidence presented in this paper indicates that the temperature swing problem does exist in some passive buildings and apparently does not exist in others. Why is this? Can it be effected by building design?

Passive solar design is now entering a new phase--a phase of design sophistication. In reaction to the overcomplexity of active systems, passive design has often been portrayed as simply a) a huge aperture to accept the south sun, b) proper shading to exclude the summer sun, and c) a really massive building to provide heat storage.

But passive solar design, done correctly, is more complex. It is a subtle complexity. The thermal design itself must be carefully considered as will be discussed in more detail in this paper. And the design must consider many factors other than

*Work performed under the auspices of the U. S. Department of Energy, R&D Branch for Heating and Cooling, Assistant Secretary for Conservation and Solar Energy Projects.

just the thermal: considerations of aesthetics, livability, economics, all leading up to the key criteria: marketability.

THE EVIDENCE

A small body of data is now emerging on passive solar heated structures. Temperature swings in two of David Wright's direct-gain passive solar homes have been documented. In the original Santa Fe home, temperature swings were observed to be approximately 20°F on sunny winter days.[1] This house has extensive south glass, a relatively large overhang, and a massive shell made of adobe walls insulated on the outside, a brick floor on sand on dirt insulated underneath, and adobe bancos containing water-filled 55-gallon drums.

Another home in Santa Fe, the second house constructed by Karen Terry, is a single-story house of somewhat more complex design. The fixed double glazing is located not only along the south wall, but in clerestory windows admitting sunlight into the back rooms. Again, there is extensive thermal mass within the thermal envelope of the building in side walls, interior walls, fireplaces, and the floor. A more comprehensive set of data have been taken on this house.[2] The instrumentation consisted of two high-low thermometers reset each day; the data acquisition system, a pencil and a notebook with records reliably kept each day. In addition to the minimum and maximum inside and exterior temperatures, observations were made of the nature of the weather on that day (clear, partly cloudy, rain, snow, windy, etc.). An analysis of this record for the winter of 1977-78 reveals the information below.

These results indicate that clear winter day temperature swings of 16-15°F average, up to 20-22°F maximum, can be expected in a building which is predominantly heated by a direct-gain passive approach, in a climate such as Santa Fe which has a high heating load and a great deal of direct sun in the winter. The only auxiliary used in this particular house is a woodburning fireplace which is used ordinarily only during periods of reduced sun and cold weather. Generally there is no auxiliary used during a sequence of clear cold days.

Another indication from direct-gain buildings has been obtained from the Wallasey school in Liverpool, England.[3] This building has also been operated without auxiliary heating; however, there is a major input of energy from the lights and the students, unlike the situation which exists in a residence. The character of the sunlight in Liverpool, England, in the winter is unlike that found in New Mexico. There are virtually no clear winter days. The neighboring North Sea dominates the weather, creating gray skies and diffuse conditions throughout the winter. Use of a diffusing glass on the south solar wall further distributes the sunlight within the building creating a relatively uniform lighting and heating condition throughout the space. Typical winter-day temperature swings in this building were observed to be 7°F, with the maximum being 16°F.[4]

Although no data records are available, it has been stated that temperature swings in direct-gain buildings in the mild southern U. S. climate of Northern Mississippi are relatively small. In such a climate little direct gain is needed in order to heat a building. Since the ratio of thermal storage to glazed area can be substantially higher, internal temperature swings can be proportionally lower.

The data record from passive solar buildings which use thermal storage walls indicates that temperature swings are less than in direct-gain structures. In almost all of these cases, thermocirculation vents were employed, as devised by Trombe and Michel. As has been noted,[5] these vents tend to create larger temperature swings in the building than would occur without the use of the vents.

Data taken on the original Trombe-Michel house in Odeillo, France, have been reported.[6] Unfortunately, the room temperature swings were not given. Since the building is 70% solar heated, presumably no auxiliary energy is required during clear winter-day conditions, regardless of outside temperature. This building is all masonry construction, except the roof; the floor is concrete slab, the side and back walls are block, and the Trombe wall is exceptionally thick (24 in.). Thus, extra daytime heating created by the thermocirculation vents, can effectively be stored in the building mass. Diurnal temperature fluctuations observed on the

Interior Temperatures, °F	Sept	Oct	Nov	Dec	Jan	Feb
Maximum	80	84	84	87	87	80
Minimum	68	66	68	63	58	59
Maximum Daily Swing	10	12	14	20	22	15
Number of Clear Days	13	27	24	19	19	15
Average Clear-day Swing	7.2	9.4	12.0	16.4	15.4	11.0
Outside Temperatures, °F						
Maximum	88	80	69	56	50	56
Minimum	37	25	10	3	8	-3

interior Trombe wall surface are almost imperceptible (~2-3°F); only the effect of longer term weather changes are observed.

Data taken by LASL in the home of Doug Kelbaugh in Princeton, New Jersey, provides additional evidence. These data indicate a temperature swing of 15°F during winter-day conditions. The house is of wood frame construction with additional mass (other than the 15-in. Trombe wall) only in the concrete floor slab of the ground floor. The thermocirculation vents are relatively large and obviously create strong heating in the building during a winter day. Passive back-draft dampers which prevent reverse thermocirculation at night, show strong air flow. Temperatures in the upstairs rooms are generally observed to be warmer than those downstairs; typically 8°F at the maximum, occurring during the late afternoon.

Data have also been taken on the two-story Trombe wall home of Bruce Hunn in Los Alamos.[7] This is an unvented solid Trombe wall 12 in. thick made of concrete block with the cores filled with mortar. It is a hybrid system in that air can be removed from the space between the glass and the wall and blown through a rock bed. During periods when the fan is not in operation, temperature swings in the room behind the Trombe wall are observed to be 9°F during sunny winter days. There is significant direct gain into the room through windows located on the side of the Trombe wall. A masonry side wall in the main room provides added heat storage.

Data have also been taken in my home in Santa Fe. This is Unit 1 in First Village, designed and built by Wayne and Susan Nichols.[8,9] It is a two-story solar greenhouse combination with the greenhouse located on the south side and the living portion on the north side of an adobe (earth brick) mass wall. The wall is 14 in. thick at the lower level and 10 in. thick at the upper level. The mass wall functions as a Trombe wall, being heated on the outside and diffusing the heat through the wall to the inside. There is no thermocirculation except as occurs through doors between the house and the greenhouse during the day. Since the staircase is in the greenhouse, there is no way air can flow from the lower level to the upper level directly. The house is a hybrid design; warm air is blown from the greenhouse to heat a rock bed underneath the floor of the living room area downstairs. Distribution of this heat to the living space is passive, by conduction of heat up through the floor slab.

Temperature swings in the greenhouse are large, typically 30 to 40°F during sunny winter days, ranging from the low 50's to the high 80's. The swing would be 10°F larger without the fan. By contrast, temperature swings in the living space are small, typically 4 to 6°F during winter conditions. This stability is attributed to the leveling effect of heat delivery from the various modes at different times. The living space is heated by direct and thermocirculation gains during the day, by diffusion of heat through the wall during the evening, and by delayed diffusion of heat up through the floor during the night. The rock-bed heating is a small contribution to the overall heating (not more than a third of the total) but adds to the comfort of the room by maintaining warm floors and stabilizing the temperature.

Extensive data from test rooms at Los Alamos have been reported.[10] Of special note are the data from water walls, Trombe walls, with and without vents, and direct gain rooms. The temperature swing information and other data are summarized in the following table.

	Thermal Storage Mass, BTU/°F per ft² glazing	Thermal Storage Surface Area/ Glazing Area	Inside Daily Temp. Swing °F	Time of Inside Temp. Peak p.m.
Direct Gain Room	39.0	3.13	38	3:00
16" Trombe Wall, (with vents)	28.6	.82	26	4:00
16" in. Solid Wall (no vents)	35.7	1.03	9	10:00
Water Wall	32.3	.66	25	4:00

These results clearly represent extreme conditions. Normally, a solar building would not be as strongly heated, in proportion to the total thermal load, as these rooms. They were intentionally designed to be strongly solar heated and generally ride from 50 to 70°F above the average outside ambient temperature during sunny midwinter days. Thus, the buildings are somewhat overheated even in the cold Los Alamos climate.

Nonetheless, the results are indicative of some general trends. The temperature stability of the unvented Trombe wall room is particularly notable. The effect of the diffusion of heat through the solid concrete is to smooth out the temperature variations. The water walls, by contrast, act as a point heat capacity and do not exhibit this delay and smoothing effect. The effect of the thermocirculation vents in the Trombe wall is to increase the daily swing, without appreciably increasing the minimum night time lows. This is partly because the buildings are of light frame construction (except for the mass storage wall) and there is no capacity to store excess daytime heat in the remaining building mass. Thus, warm air delivered by thermocirculation to the room increases its temperature during the day. This increases the heat which is stored on the back side of the wall because of the warmer room temperature but also decreases the outside wall surface temperature by about 20°F due to the thermocirculation, thus decreasing the heat absorbed into the wall from the front face.

CONTROL OF TEMPERATURE SWINGS

Control using Auxiliary Backup Heating and Ventilation

The control of many passive buildings works roughly as follows: 1) anytime the temperature is below a predetermined level, the auxiliary is turned on; 2) anytime the temperature is above another set level (presumably somewhat higher), the windows are opened, or an automatic ventilating fan is turned on. Temperatures are thus maintained roughly within the set limits. The main problem with this approach is that it vents useful energy to the outside at times and thus increases the amount of auxiliary required at a later time. Increasing the difference between the temperature control set points increases the solar heating contribution because internal heat storage is proportional to the temperature swing.

The auxiliary heating system provides temperature control by supplying the difference between the building load and the energy supplied by solar heating and internal sources. This is operative only while the auxiliary is on and thus becomes less effective as a control method as more of the total heat is supplied by solar. Control by this means alone is insufficient for lightweight buildings with more than 30 to 40% solar heating. As more mass is added to the building the range of effectiveness is extended.

Ventilation is recommended as a means of controlling against building overheating only in the spring and fall when there is net excess energy available and auxiliary heating is not required during sequences of sunny days.

Natural control, without resort to auxiliary or ventilation should be built in to the greatest extent possible. This is described below for the various classes of passive solar construction.

Direct Gain

This is the most popular passive solar design approach due to simplicity and perceived low cost. The main problem is providing sufficient thermal storage to control temperature swings within acceptable levels. The cost of the glazing is no more than that of the wall it replaces, but thermal storage is expensive. Other problems are strong directional daylighting, glare, and ultraviolet degradation of fabrics.

Intrinsically the building interior must vary in temperature if its surrounding surfaces are to store heat. The occupants of many of these buildings are so delighted to be warm in the winter that they do not complain of being too warm occasionally. The bulk of the American public may not be so easy to please.

Heat may be stored on the interior building surface in side walls, in the floor, in the ceiling, or in special thermal storage elements placed within the building interior. Each of these has its own special character.

Although heat storage in the floor is economical, it is known to be relatively ineffective unless the floor is of masonry construction, is uninsulated on the surface, and is located in the direct (unshaded) sun.[11] This is a severe requirement, seldom met. People like to put rugs, furniture, potted plants, teddy bears, and other things in their living space.

We are now obtaining data on test rooms and on several direct-gain passive structures. The plot in Fig. 1 shows the temperature on the floor in a Santa Fe house which LASL is monitoring.

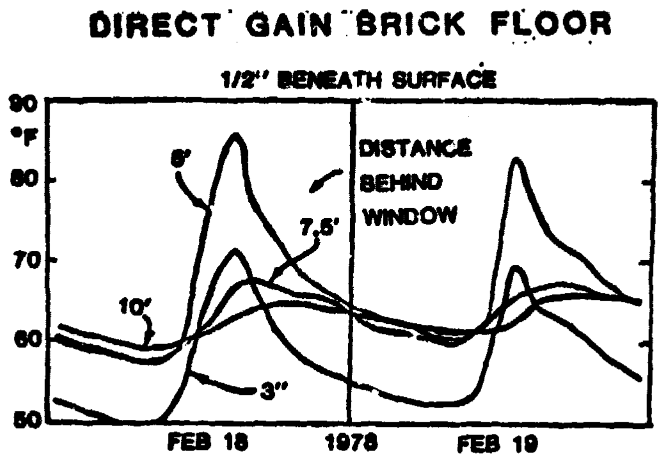

Fig. 1. Floor temperatures measured in a direct-gain house along a line extending north from the windows. The shadow line is about 5' 9". The measurement at 3" is low due to cold air falling down the window.

Thermal storage in side walls is also difficult because they are seldom located in the direct sun. Thus, extensive and expensive mass must be deployed. Thermal storage in the roof would be very effective because of the tendency of heat to gravitate upwards towards it. This has not been used extensively, however, and has obvious structural requirements. The phase-change roof tiles being experimentally developed at M.I.T. may be an advance in this direction.[12] Another interior mass roof possibility which could be used is a thin concrete slab poured over a metal roof deck or earth on a metal deck.

The property of a wall to store heat through a surface and return that heat back through the same surface is called "thermal admittance."[13,14] Formally, the thermal admittance is the ratio of heat flux to temperature swing when each of these functions are sinusoidal. For purposes of analyzing heat storage in walls, it is reasonably accurate to assume that the temperature varies sinusoidally on a daily basis. The diffusion of heat through most wall materials is sufficiently slow that one must account for the fact that material deep within the wall is relatively ineffective for temperature heat storage on a daily basis. The surface layers insulate the layers at depth. Another important consideration is the relatively large impedance for heat flow from the room air to the wall surface. This is important if the sun energy is first transferred from lightweight surfaces in the room (such as rugs, furniture, etc.) to the warm air and then from the room air to the wall surface.

Work done by Mazria, Wessling, and Baker,[15] shows the desirability of distributing the mass over as large a surface area as possible. They show that distributing the same mass over nine times the window area rather than one and one half times the window area would reduce the temperature swing in one case from 43°F to 12°F. Their analysis is based on the assumption that the energy can be distributed over this extended surface. Although it is doubtful that this assumption can be realized in practice, the trend indicated is certainly correct. If the sunlight can be diffused and scattered to more uniformly illuminate a larger interior mass surface, this will certainly reduce the temperature swings.

One way of accomplishing this is to use a diffusing glazing. This was done in the Wallasey school in Liverpool, England.[3] In this case the inner vertical glazing was a "figured" glass imported from Belgium. The glass scattered the sunlight onto the ceiling, back walls and side walls, which were all of concrete. As noted earlier, the temperature swings are reasonably small.

Other possibilities are the use of a translucent fiberglass-acrylic, which is frequently used for glazing greenhouses, swimming pool room covers, etc. The transmissivity of these materials can be quite high, yet they act to diffuse the light. Glass which has a mottled or ripply surface, such as that frequently used in bathrooms, can have the same effect.

As a general principle, materials in the room which have little heat storage capability should be light in color. To some extent, it is also desirable to make mass storage walls dark in color. This is especially true if they are in the direct sun. However, extensive use of dark surfaces in interior spaces will result in a lightless and dim room, and extra energy will then have to be used to light the room. This is clearly self-defeating. Thus, in the Wallasey school, all the interior mass walls are painted white to more uniformly diffuse the light throughout the room and reduce the need for artificial illumination.

The use of a white paint on interior mass surfaces is less serious than one might expect. Much of the sun energy entering the room is converted to infrared, which is subsequently radiated throughout the room. All paint and most materials have a high absorbance for infrared radiation (∿ 90%) even though they are a diffuse reflector in the visible spectrum.

Thermal Storage Walls

Like all indirect passive solar heating approaches, the thermal storage wall circumvents two of the major difficulties with the direct gain approach, both associated with admitting sun into the living space: the high lighting levels, and damage to materials in the building by the ultraviolet. Placing windows in the thermal storage wall, as was first done by Doug Kelbaugh and later by others, is one effective means of mixing design approaches. Another major advantage of the thermal storage wall is the reduction of temperature swings by interposing a capacity effect between the solar gain and the living zone. This is especially true if the thermal storage wall is a solid material, such as concrete, which provides a dramatic smoothing of the temperature wave as it diffuses through the wall. Data given for the LASL test rooms indicate this effect.

Another advantage of a solid thermal storage wall is providing a time delay between the absorption of solar energy on the outside of the wall and the delivery of that energy to the interior of the building. Characteristically, this time delay is on the order of six to twelve hours so that the maximum heating generally occurs in the evening at a time when it is most needed in a residential application. This time delay effect is quite evident in every thermal storage wall which LASL has monitored. Figure 2 shows data taken at different points within the thermal storage wall in Bruce Hunn's home.[11] Two things should be noted on this plot: the increase in time delay of peak temperature, and the decrease in the peak temperature as the wave progresses through the wall.

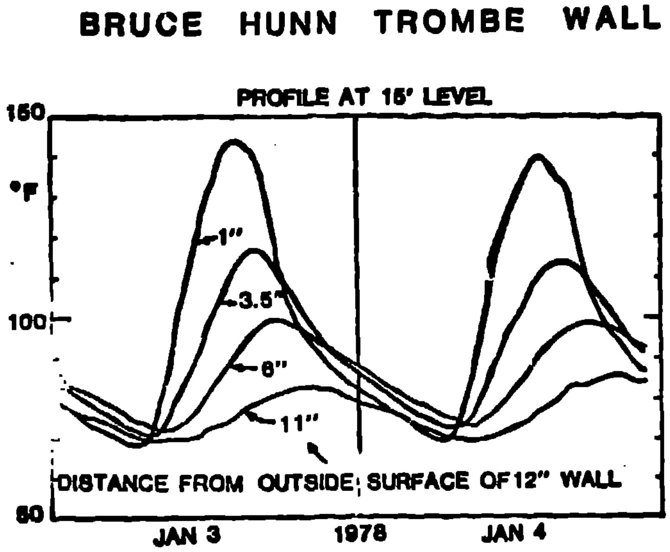

Fig. 2. Temperatures measured in a two-story thermal storage wall. The wall is made of 12" hollow concrete block with holes filled with mortar. The wall is double-glazed and has no vents.

The time delay effect allows for flexibility in thermal design. The building can be heated by direct gain of thermocirculation during the day and by the wall at night. The following table lists the characteristics of a solid concrete wall during sunny days with double glazing on the outside:

Thickness, Inches	Inside Surface Temperature Swing	Time Delay of Peak on the Inside
8	40°F	6.8 hrs
12	20°F	9.3 hrs
16	10°F	11.9 hrs
20	5°F	14.5 hrs
24	2°F	17.1 hrs

The thickness of solid wall, which gives the maximum annual energy yield to the building, is about 12 in., independent of climate.[16] However, such a wall has rather large temperature swings and tends to be cold and uncomfortable during long cloudy periods.[7] Thus, the designer is led to consider thicker walls which provide more storage and a more stable inside surface temperature.

Water walls have frequently been considered as an attractive design alternative to concrete. The basic difficulty is the physical containment of the water. Metal, plastic, concrete, and fiberglass containers have all been used. One should be aware that the time phasing characteristics of the water wall are rather different than that of the unvented Trombe wall. Since the water convects to effectively transport the heat across the heated side to the room side, there is no effective time delay in a water wall. The peak temperature occurs just at sundown.

Thermal stability is achieved through the use of very large storage masses. The main advantage of the water wall is the ability to greatly increase the thermal storage capacity of the passive building without excessive use of space.

Solar Greenhouses and Sun Spaces

A solar greenhouse is a mixture of the direct gain and thermal storage wall approaches. It is a subset of the more general design approach which might be termed a "sun space." It generally consists of a direct-gain space adjacent to another space which is on the north side of the building.

This general design approach is of great interest because it can be used to reduce temperature swings in a portion of the building and stabilize the temperatures. The general approach is shown in Fig. 3. The building can be considered in two zones. In Zone 1, which is the direct-gain space, large swings in temperature can be anticipated. Thermal storage is in the mass wall separating Zone 1 and Zone 2 and also in the floor of Zone 1. The principal advantage of the approach is the reduced temperature swings in Zone 2. This is a buffered space which is protected from the extremes of Zone 1 by the time delay in heat capacity effects of the mass wall. With a little care in thermal design, one can arrange to phase the heating of Zone 2 so as to maintain a nearly constant temperature.

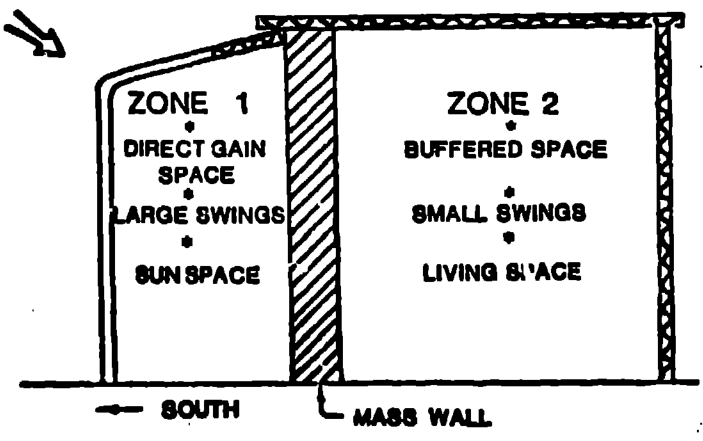

Fig. 3. Buffering of temperature swings in the living space by means of a two-zone structure. Hot air from Zone 1 can also be blown through a rock bed under the floor of Zone 2.

Since the temperature swings in Zone 1 tend to be relatively large, typically 30 to 35°F during winter clear-day conditions, it becomes attractive to remove some of the day time excess heat by blowing air from the sunspace to a place where it can be stored or used. This has been done by Migel in his Tesuque solar greenhouse, and by the Nichols' in First Village, Unit 1. In these two cases the heated air is blown through the underfloor rock bed. Subsequent heat distribution to the home is passive, by conduction up through the floor slab.

These hybrid designs have worked very well, increasing comfort levels. They greatly increase the thermal storage utilization of the floor slab and are not too costly since the underfloor space is free for the digging and the rocks can support the floor slab. The principal design considerations are: 1) use a sufficient air flow to move the required heat at the low ΔT's available, 2) use a high flow, low-pressure squirrel-cage fan to obtain high efficiency and quiet operation, 3) lay out the rock beds with their inlet and exit plenums in such a way as to match the rock bed pressure drop to the fan characteristics, 4) make sure that the air flows through all the rocks, and 5) return the air to the sunspace. Since the rock bed operates at low temperature, it is not necessary to insulate it except at the edges where heat would be lost to the outside. The earth under the rock bed adds to its heat storage effectiveness. Foundations can double as plenum walls and will themselves store a small amount of heat if the perimeter insulation is placed outside.

Hunn uses a similar scheme. In his case the "sunspace" is only 6 in. thick (the space between the glazing and the Trombe wall) and the rock bed is thermally remote. This has not worked well since the temperatures achieved are low and do not match well with the temperatures needed for his forced-air distribution system. He proposes reducing the (charging mode) air flow rate to increase the temperature.

Natural thermocirculation of air from the sunspace to the living space is a normal approach used for both Trombe walls (a form of skinny sunspace) and solar greenhouses. Upper and lower vents are opened and a strong thermocirculation is set up during the day. This should be used up to the point that the heat can either be used or stored within the living space. The diurnal heat storage capacity of the living space can be estimated using the table given earlier. The values used should be those in the column marked "indirect, $\Delta Q/\Delta T_{room}$." The floor beneath the living space is totally ineffective for indirect heat storage in this manner and should not be counted.

Convective Loops

Natural convective loops have been discussed above as used in Trombe walls and greenhouses. This concept can be extended to the case of a large solar collector area and rock bed storage thermally remote from the heated space. This has been done by Baer in the Paul Davis house,[17] by Jay Davis in several houses, and by Mark Jones.

This approach provides the possibility of a high degree of control since the storage can be thermally isolated from heated space or connected to it at will. The Paul Davis house uses passive distribution with manually controlled dampers. The Mark Jones house uses a conventional (active) forced-air distribution system with the rock bed lower plenum connected to the return air plenum and the furnace fan inlet connected to the rock bed upper plenum. Both seemingly work quite well.

Isolated Storage

A variety of design options provide a high degree of thermal isolation between thermal storage and the conditioned space. The convective loops referenced above are examples and many others exist. The "solar battery" by Kalwall is one. A water wall made of fiberglass tubes is contained and insulated on the backside and air is blown through a thermostatically controlled fan. The Benedictine Monastery water wall is very similar except that the distribution is passive and the control is provided by the office occupants by opening or closing manual vents.[18]

The main motivation for isolated storage would seem to be a desire to obtain a high degree of thermal control. Many possibilities exist; for example, a curtain or adjustable louver could be put between a thermal storage wall and the adjacent space. In the long run the simple, reliable, and passive approaches will probably prevail over their mechanical, expensive, and active alternatives.

REFERENCES

1. B. T. Rogers, "Some Performance Estimates for the Wright House--Santa Fe, New Mexico," pp 189-199, Passive Solar Heating and Cooling, Conference Proceedings, May 18-19, 1976, Albuquerque, NM.

2. Homeowner, Private Communication.

3. J. D. Perry, Jr., "The Wallassey School," pp 223-237, Passive Solar Heating and Cooling, Conference Proceedings, May 18-19, 1976, Albuquerque, NM.

4. M. G. Davis, "Heating Buildings by Daylight," Building Technology and Management, 8, 2-5, (1970).

5. J. D. Balcomb, R. D. McFarland and S. W. Moore, "Simulation Analysis of Passive Solar Heated Buildings--Comparison with Test Room Results," ISES Annual Meeting, June 1977, Orlando, FL.

6. F. Trombe, J. F. Robert, M. Cabanet, and B. Sesolis, "Some Performance Characteristics of the CNRS Solar House Collectors," pp 201-227, Passive Solar Heating and Cooling, Conference Proceedings, May 18-19, 1976, Albuquerque, NM.

7. B. D. Hunn, "A Hybrid Passive/Active Solar House: First Year Performance of the Hunn Residence," 2nd National Passive Solar Conference, Proceedings, March 16-18, 1978, Philadelphia, PA.

8. W. Nichols, "Unit 1, First Village," Passive Solar Heating and Cooling, Conference Proceedings, May 18-19, 1976, Albuquerque, NM.

9. R. D. Stromberg and S. O. Woodall, "Passive Solar Buildings--A Compilation of Data and Results," SAND-77-1204, August 1977.

10. J. D. Balcomb, R. D. McFarland, and S. W. Moore, "Passive Testing at Los Alamos," 2nd National Passive Solar Conference Proceedings, March 16-18, 1978, Philadelphia, PA.

11. J. D. Balcomb, "State of the Art in Passive Solar Heating and Cooling," 2nd National Passive Solar Conference, Proceedings March 16-18, 1978, Philadelphia, PA.

12. T. Johnson, "Preliminary Performance of the M.I.T. Solar Structure," 2nd National Passive Solar Conference, Proceedings, March 16-18, 1978, Philadelphia, PA.

13. M. Jacob, Heat Transfer, Vol. 1, pp 292-304, Wiley, (1949).

14. M. G. Davis, "The Thermal Admittance of Layered Walls," Building Science, Vol. 8, pp 207-220, Permagon Press, 1973, Printed in Great Britain.

15. E. Mazria, M. S. Baker, F. C. Wessling, "Predicting the Performance of Passive Solar Heated Buildings," pp 89-99, Solar Architecture, Ann Arbor Science (1977).

16. J. D. Balcomb, "State of the Art...," pp 3 (see Ref. 11).

17. P. Davis, "To Air is Human," Passive Solar Heating and Cooling, Conference Proceedings pp 40-45, May 18-19, 1976, Albuquerque, NM.

the alpha-particle thermalization constraint still requires substantial B^2-(ignition) values.

In general, alpha-particle heating for LMF devices is a crucial issue from both the view point of heating and confinement. Unfortunately, because of the theoretical difficulty in analyzing thermalization processes in finite geometries, this aspect of reactor-related plasma and energy balance modeling has received only cursory treatment to date.

C. Stability and Equilibrium

Hot and dense plasmas produced in straight solenoidal geometries have been shown both experimentally[60,61] and theoretically[31,32] to exhibit radial equilibrium and neutral stability. The m = 1 "wobble" MHD instability, which is believed to be induced by partial shorting of radial electric fields in the plasma at the end region,[62] saturates at a low amplitude, is not observed for large radius plasmas (radius approximately equal to half of the wall radius), and is completely damped by the use of a MEP.[27] Recent theoretical work[63] indicates that finite-Larmor-radius effects are responsible for the stabilization of higher mode rotational instabilities. Although LMF devices generally should be stable to non-ideal MHD rotational instabilities, the question of curvature-driven instabilities (ballooning and interchange modes), such as those expected at high beta in multiple mirror configurations, is unclear; finite-Larmor-radius and wall-stabilization effects may play an important stabilizing role, but some form of feedback or dynamic stabilization may be required. Although the simple theta-pinch configuration permits operation outside the plasma parameter range where resistive and collisionless tearing modes are active, LMF approaches that operate with trapped or reversed field may have to deal with this problem.

In summary, although the characteristic of neutral stability for LMF is generally valid, this claim must be examined more carefully in the context of the specific heating and axial confinement schemes being proposed. For instance, beam-driven instabilities which enhance radial field or particle transport may become crucial for LMF concepts that require very small radii plasmas. Other anomalous phenomena related to the particular heating scheme may also reduce the final plasma beta, thereby diminishing the overall efficiencies projected for specific LMF reactor embodiments.

III. SUMMARY DESCRIPTION OF LMF FUSION REACTOR CONCEPTS

The essential elements of most LMF approaches to fusion power are determined in large part by the benefits and limits of particular confinement and heating schemes invoked. The intent here is to present only a qualitative summary of each design as they presently exist; the variability in study level, physics assumptions, and projection of certain technologies all combine to make a quantitative comparison inadvisable at this time. An emphasis is placed, however, on both the general merits and problems anticipated for each approach. The results of an ongoing comparative assessment by Electric Power Research Institute and Bechtel Corporation[64] on the basis of economic and technology guidelines, however, should be of significant value in making a more quantitative assessment. It is also noted that of the seven LMF concepts reviewed here only the Laser Heated Solenoid (LHS)[5,6,41] and the Electron-Beam Heated Solenoid (EBHS)[4,52] reactors have received indepth study, although a significant part of the toroidal Reference Theta-Pinch Reator (RTPR) study[47,46] is applicable to the Linear Theta-Pinch Reactor (LTPR)[8] concept. Since the few reactor design parameters cited are based on either interim or older values, they should be viewed only as indicative, and no comparative assessment is implied or intended.

A. Laser-Heated Solenoid (LHS)[5,6,38,41]

Because of previously noted limitations on coupling 10.6-μm laser light to the plasma and the desire to minimize both total laser energy (50-75 MJ) and reactor length ($\lesssim$500 m), the LHS envisages at least four small bore (.05-m radius first wall) plasma chambers embedded into a ~1.5-m radius blanket. The $2.0(10)^{23}$ m^{-3} dense plasma is heated to 1.7 keV by laser absorption that is enhanced over the predictions of inverse-bremsstrahlung absorption by a factor of 10; multiple-pass heating is proposed. The 28-T compression field that brings the plasma to a ~18-mm ignition radius is generated by nulling an 18-T superconducting field with a normal, room-temperature coil located immediately behind the first wall. The firing sequence for a nominal 20-ms burn pulse is shown in Fig. 6, and a 4-s dwell time between sequential burn pulses in each of the four plasma chambers is envisaged. In order to achieve a 20-ms burn in a 500-m long device, an unspecified axial confinement was assumed to an extent that allows the burn to occur for ~8 free-streaming endloss times or ~4 thermal conduction times (if a MHP was employed). The pulsed normal magnet requires 1.3 GJ of homopolar motor/generator storage,[45] and 770 MWe(net) of electricity at 3.4 MW/m^2 fusion neutron wall loading is produced with a recirculating power fraction of 0.25 and a total system power density* of 0.35 MWt/m^3. The advantages of a decoupled pre-heating source (i.e. the laser), the possibility of high-field LMF in the small-bore coils, and the relatively high plasma filling fraction (reduced magnetic energy storage and transfer requirements) must be weighed against the problems and/or uncertainties associated with severe thermal pulses and neutron doses at the first wall magnets, the unresolved end-stoppering and laser-absorptivity factors, the large laser energy and power densities (50-75 MJ, 10^{14}-10^{16} W/m^2), and the lower margin allowed for the effects of anomalous radial transport.

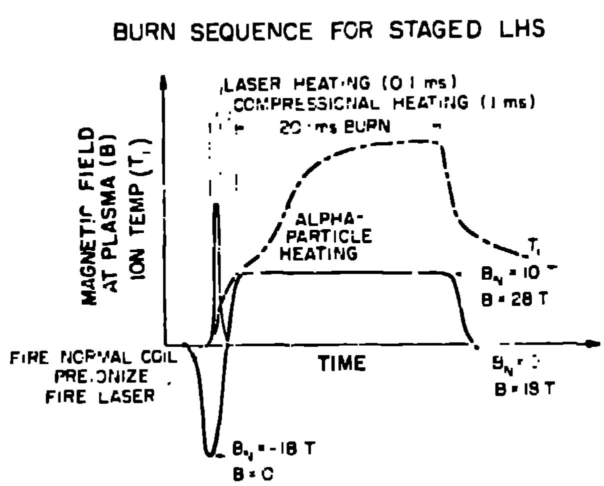

FIGURE 6. Typical burn cycle for a staged Laser Heated Solenoid (LHS) using axial confinement that is 10 times better than free streaming.

B. Electron-Beam Heated Solenoid (EBHS)[4,52]

The EBHS concept proposes the injection of a ~30-MJ, 10-MV REB into a plasma of 17-mm radius and 275-m length to provide the total heating required for ignition. The 80% efficient REB source would deliver a total current of 0.45 MA (500 MA/m^2) along a 5.9-T guide field; the 15.3-T confining field would be produced by superconducting coils. The 384 MWe(net) power is achieved with a recirculating power fraction of 0.35 and a 260-ms pulse period to give a first-wall fusion neutron wall loading of 4 MW/m^2 from the single plasma chamber. The total system power density is 0.73 MWt/m^3.

The burn cycle proposed for the EBHS, as illustrated in Fig. 7, would inject along a guide field cold plasma (few eV) from annular plasma guns located co-axially with and in front

*Defined always as the total thermal power divided by the volume enclosed by the confinement system.

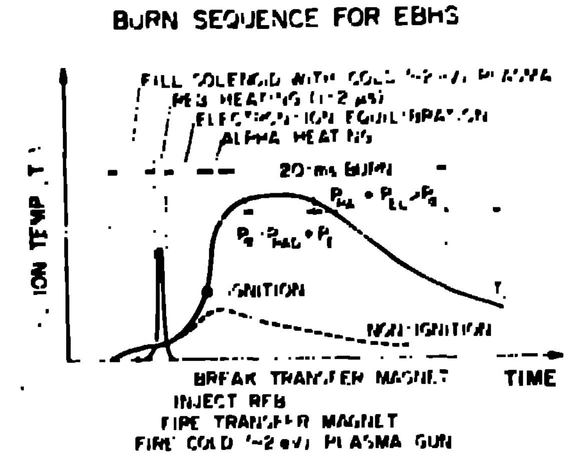

FIGURE 7. Typical burn cycle for an Electron Beam Heated Solenoid (EBHS) using multiple mirror confinement.

of the REB diode structure at each end of the device. After radially expanding the guide field to the vicinity of the annular REB diode by means of a transfer magnet, the REB is guided along the magnetic field lines into the plasma chamber after being compressed by a factor of 10. The transfer magnet then forces in ~1 ms the solenoidal fields radially inward and through the annular REB cathode to protect that part of the REB apparatus from the eventual plasma [illegible]. The REB energy is assumed to be uniformly deposited along the interaction length given by Eqn. (11) to an extent sufficient to cause a stationary burn (alpha-particle deposition equals radiation losses). The 20-ms high beta burn period at $2.1(10)^{22}$ m^{-3} density is assumed to occur uninhibited by endloss through the use of feedback stabilized multiple mirrors; a scaling similar to that given by Eqn. (6) is used, with the assumption of non-adiabatic scattering in the presumed very sharp mirrors. The vacuum mirror ratio was taken to be 2, although the effective, high-beta mirror ratio could be as high as 4-6. Streaming plasma from the EBHS ends passes through the central hole in the annular REB cathode and must be expanded in radius by a factor of 500 to suppress secondary electron emission from and thermal [illegible] the [illegible] endplates.

The unique feature and [illegible] attraction of the EBHS approach is the [illegible] of the efficient primary (REB, 30 MJ) and secondary (plasma gun, 2-3 MJ) heating sources from the confinement system. This advantage is reflected by the fact that the EBHS achieves recirculating power fractions that are comparable to other pulsed LMF approaches, but with a [illegible] the [illegible] value. The required REB compression and [illegible] port, the general stability and [illegible] the REB-plasma interaction [illegible] beam diffusion and dispersion, absorption [illegible] unresolved issues associated with the target plasma formation, the overall effective [illegible] and stability of high-beta multiple mirrors, the feasibility of thermally stable burn, and the question of radial plasma transport [illegible] however, present uncertainties for this [illegible].

C. Linear Theta Pinch Reactor (LTPR)

The heating and (radial) [illegible] principles for the LTPR would be identical to those envisaged for the toroidal Reference Theta Pinch Reactor[42,55] were it not for the rapid loss of plasma energy from the open ends. Hence, a pre-ionized D-T [illegible] heated [illegible] (~1 [illegible]) implosion (~0.1 MV/m azimuthal [illegible]) electric field to temperatures of ~1 keV. This preheated plasma is subsequently compressed adiabatically to ignition temperatures (~5 keV), and a burn cycle occurs along a plasma radius/temperature trajectory determined primarily by the dynamics of an energetic, high-beta plasma. The LTPR [illegible] REP, wherein the endloss particles and energy emanating [illegible] LTPR [illegible] directed by a small radius-of-curvature conduit to a second, parallel plasma column. The plasma within the REP region may not necessarily be in "toroidal" equilibrium and will be subject to cross-field transport losses. An intermittent toroidal equilibrium may be established in the REP region which is similar to that envisaged for the

FRTR,[10] [illegible] a [illegible] first wall [illegible]. The REP is assumed to [illegible] 3.5 MeV alpha particles. A typical LTPR burn cycle as determined by a time-dependent, two-particle, 1-D (axial) burn and energy balance code, LTBURN, is depicted in Fig. 8, which also lists key operating parameters. With a [illegible] power fraction of [illegible], a 2-MW/m² [illegible] neutron wall loading would result in a net electrical power of [illegible] MWe(net), a system power density of [illegible] MWe/m³, and a pulse frequency of 0.08 Hz [illegible]. The [illegible] device uses a [illegible] m radius REP with a cross-field thermal conductivity [illegible] both the [illegible] and adiabatic compression coils are [illegible] first wall and [illegible] operated [illegible] require [illegible] GJ and [illegible] GJ of pulsed energy delivered in [illegible] and [illegible] ms, respectively; reversible recovery of the adiabatic compression energy at 95% efficiency is specified.[illegible] [illegible] relieve [illegible] associated with pulsed thermal [illegible] of the first wall energy

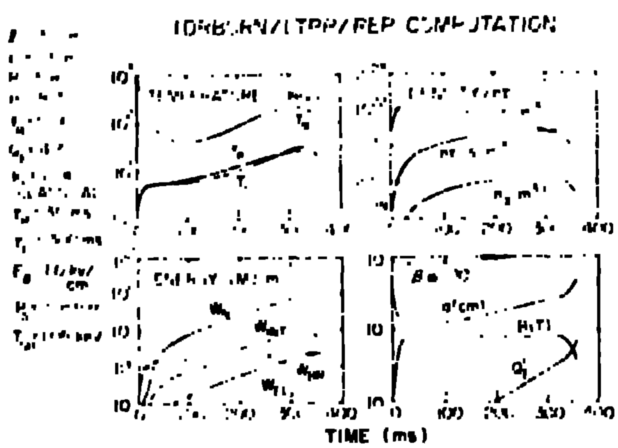

FIGURE 8. Typical burn cycle for a Linear Theta Pinch Reactor (LTPR) using re-entrant endplugs.[3]

[illegible] and magnet stresses (8 T peak field). The present [illegible] of the REP [illegible] of the implosion [illegible] (high-voltage [illegible] blanket and first wall are required), [illegible] the need for a [illegible] efficient (95%) energy transfer and storage system represent crucial issues for the LTPR.

D. Linear Imploding Liner (LINUS)[12]

The LINUS approach to MFE attempts to achieve high-beta plasmas of $2\text{-}3 \times 10^{23}\ m^{-3}$ (B ≈ 64 T) density. The high densities and fields are produced reversibly by driving with gas pistons a rotating (3 Hz) liquid-metal cylinder (1.6-m inner radius, 1-m thick, 12-m long) radially inward onto a low temperature plasma ($2.5 \times 10^{21}\ m^{-3}$, ~1 keV) and guide field. The plasma and guide field are compressed by a factor of 100 within ~25 ms, and the burn period is sustained by the inertia of the LiPb liner before it reversibly "bounces" radially outward towards its starting position. Hence, adiabatic compression represents the major heating mechanism, and a major portion of the ~6 GJ initial radial kinetic energy (which must also supply the final rotational energy as angular momentum is conserved) must be reversibly recovered. The alpha-particle pressure generated during the burn is more than enough to compensate for liner losses and to assure a reversible cycle. Approximately 1.5 GJ of thermonuclear energy would be released, and the pulse frequency would be ~1 Hz. The liner is driven by a 24 MPa (3500 psi) gas reservoir, which under reversible operation serves as the primary energy store.

For the peak compression field (64 T) and LINUS length (12 m), a nearly closed axial confinement will be required (re: Fig. 2). A rotating, hollow REB (40 MJ, 3 MA, 3 MW, 4 μs) is injected into one end of the device, which breaks down the gas, preheats the plasma, generates the precompression fields, and upon exiting the device leaves residual plasma suggests that the [illegible] a closed, reversed field [illegible] way with efficient preheat, [illegible] field alignment are achieved by [illegible] FSS energy source that is only loosely coupled to the reactor core. The capacitors system power density equal 13.5 MW/m³ and the regenerated first wall represent other attractions of the LINUS concept. Major questions for this IMF approach are associated with the plasma and [illegible] preparation, the efficiency with which the liner energy can be reversibly recovered, and the general technology required to reversibly implode once a second a [illegible] (135 tonnes) rotating liner system.

E. Fast Liner Reactor (FLR).[11,40]

Unlike the LINUS approach,[12] the FLR attempts to eliminate the need for reversible and controlled recovery of the liner energy, which may equal or exceed the thermonuclear output. The FLR approach envisages a small liner system (initially ~ 0.1 0.3 m radius and length) that is rapidly (~ [illegible]) driven into a preheated and dense (~500 eV, ~10^{25} m^{-3}) plasma with sufficient speed (~10^4 m/s) and energy (400-500 MJ) a) to operate with [illegible] thermonuclear yield per unit of initial liner energy (high Q), b) to eliminate the need for liner rotation (for stabilization of Rayleigh-Taylor hydrodynamic modes), and c) to open the possibility of wall (inertial) confinement in the presence of a thermally insulating magnetic field. Hence, adiabatic compression supplies the major heating for the FLR, preheating can be provided by plasma-gun injection, and the axial (and radial) confinement falls into the HEP (with magnetic insulation) category. The advantages cited for the LINUS also apply to the FLR which has a system power density of 9.3 MW/m³, a pulse rate of 10 Hz, a net power of 270 MWe(net), and a recirculating power fraction of 0.25. To circumvent the potential LINUS problems of reversible energy recovery, heating and confinement, the faster operating mode for the FLR [illegible] materials [illegible] (heating and storage).

F. Dense Z-Pinch Reactor (DZPR)[illegible]

The DZPR is proposed as another means to achieve a very compact [illegible] plasma. A [illegible] self-constricting current [illegible] ~1 MA [illegible] (~2 GA/m²) is proposed [illegible] 40 MJ, 40 MW [illegible] supported [illegible] dense gas [illegible] previously [illegible] classical breakdown. [illegible] Larmor radius [illegible] large [illegible] currents may be [illegible]. Resistive heating would be provided [illegible] compression [illegible] the [illegible]. The [illegible] Z-pinch [illegible] efficiently providing [illegible] heating and confinement, [illegible] experimental constraints, [illegible] plasmas of ~10 m [illegible] have been reported [illegible] with [illegible]. Stabilization against the [illegible] sausage instabilities by gas embedding [illegible] flow or finite Larmor radius effects may be feasible.[16,illegible] Although the problems of blast confinement and energy transfer [illegible] are not unlike those noted for the FLR and certain beam-pellet fusion schemes, the more elegant configuration offered by a stabilized, self-constricting pinch represents a major attraction.

G. Steady State (Solenoidal) Fusion Reactor (SSFR)[11,68,illegible]

It seems appropriate to conclude this survey with an IMF scheme that in principle promises to fulfill the two most cherished goals of fusion research: a) simple physical and magnetic geometry, and b) steady-state operation. The [illegible] near the [illegible] "ig [illegible]" [illegible] the [illegible], [illegible] plasma [illegible] steady state [illegible] [illegible] [illegible] for the RFP [illegible] over [illegible] range of [illegible] [illegible] that the product of [illegible] M [illegible] length [illegible] not exceed [illegible], and the maximum total fusion power [illegible] was [illegible] W, where [illegible]. A [illegible] and [illegible] very large systems [illegible] [illegible].

[illegible] [illegible] power required [illegible] [illegible]. The possibility of such [illegible] operation has been [illegible] in which a 4000 MW [illegible] [illegible] power fraction of [illegible] length [illegible] [illegible]. Computations for the LIPR with a RLP, similar to those given on Fig. 8, also show the potential for quasi-steady-state operation, wherein axial density and temperature profiles are maintained [illegible] radial field diffusion[12] becomes important.

IV. SUMMARY AND CONCLUSIONS

The major constraints imposed on LMF by the physics of heating and confinement have been discussed, and the impact of these constraints on a wide range of conceptual LMF reactors designs was reviewed. Two generic approaches to [illegible] are ultimately [illegible] issues. First, [illegible] under 1000 m [illegible] densities [illegible] will require a level of confinement equal to that projected for either multiple mirrors or [illegible] (and possibly reversed field [illegible]), a number of approaches to high-beta MM or RLP confinement [illegible] be explored and each generally [illegible] the issue of plasma stability as a trade for axial confinement. Secondly, the high field LMF approach retains the advantages of neutral [illegible] and attempts to "outrun" the axial confinement problem by means of the B^2 [illegible] In setting this course high field LMF [illegible] to address the technological problems of high field magnets and high heat flux first walls [illegible] for well understood and predictable [illegible]; the imploding liner and [illegible] Z-pinch approaches promise a unique solution to the high heat flux wall problem. At this stage in the development of fusion power, both approaches seem justified. Ultimately the advantages of LMF [illegible] may be realized by a synthesis of results that emerge from experimental and theoretical studies of both approaches.

V. ACKNOWLEDGMENTS

The author wishes to express his gratitude and appreciation to the following people who have reviewed and contributed to this review: R.L. Miller, R.L. Hagenson, R.F. Gribble, K.E. McKenna, R.J. Commisso, and W.E. Quinn (LASL); L.C. Steinhauer (MSNW); R.S. Cooper and T.S.T. Young (PI); A.E. Robson (NRL), and C.W. Hartman (LLL).

VI. REFERENCES

(1) USDOE Special Report, "Linear Magnetic Fusion: A Summary of the Workshop Held at Seattle, Washington," March 9-11, 1977, CONF-770386.

(2) G. Sawyer (ed.), "Workshop on End-Stoppering of Linear Magnetic Fusion Systems," October 12-14, 1977, Santa Fe, NM (to be published).

(3) B.G. Logan, I.G. Brown, A.J. Lichtenberg, and M.A. Lieberman, "Plasma Confinement in Multiple Mirror Systems II, Experiment and Reactor Calculation," Phys. Fluids, 17, 1302 (1974).

(4) J. Benford, T.S.T. Young, B. Ecker, D. Dakin, I. Smith, S. Putnam, and V. Bailey, "Electron Beam Heating of Linear Fusion Devices," Proc. 1st International Topical Conf. on Electron Beam Research and Technology, November, 1975, Albuquerque, NM.

(5) A. Hoffman, P. Rose, L. Steinhauer, "Status of Laser Solenoid Fusion Concept," Trans. Am. Nucl. Soc., 27, 49 (1977).

(6) L.C. Steinhauer and G.C. Vlases, "Fusion Reactor Concepts Based on the Staged Laser Solenoid," Nucl. Fus. (to be published, 1978).

(7) J.P. Freidberg, et al., "Review of the Linear Theta Pinch (LTP) Concept," USERDA Rept. LA-UR-77-961 (April, 1977).

(8) R.A Krakowski and R.L. Miller, "Reactor Plant Design Study for Alternative Concepts: A Preliminary Report on the Linear Theta-Pinch Reactor (LTPR) Concept," USDOE Rept. LA-UR-78-180 (1978).

(9) A.R. Jacobson, C.J. Buchenauer, J.N. Downing, and K. Thomas, "Auxiliary Heating of a Theta-Pinch Plasma by Radial Magnetoacoustic Standing Waves," Phys. Rev. Lett., 37, 14, 897 (1976).

(10) R.W. Moir, et al., "The Tandem Mirror Reactor," Technical Committee Meeting and Workshop on Fusion Reactor Design, October 10-21, 1977, Madison, WI, to be published in Nucl. Fus. (1978).

(11) A. Hasegawa, T. Hatori, K. Itoh, T. Ikuta, Y. Kodama, and K. Nozaki, "Concept of a Fusion Burner," Nucl. Fus., 16, 5, 865 (1976).

(12) A.E. Robson, "A Conceptual LINUS Fusion Reactor," Trans. Am. Nucl. Soc., 27, 45 (1977).

(13) R.A Krakowski, R.W. Moses, R.L. Miller, and R.A. Gerwin, "Fusion Power From Fast Imploding Liners," Technical Committee Meeting and Workshop on Fusion Reactor Design, October 10-21, 1977, Madison, WI, to be published in Nucl. Fus. (1978).

(14) C.W. Hartman, G. Carlson, M. Hoffman, and R. Werner, "A Conceptual Fusion Reactor Based on the High-Plasma-Density Z-Pinch," Nucl. Fus., 17, 5, 909 (1977).

(15) A.J. Lichtenberg, M.A Lieberman, and B.G. Logan, "Multiple Mirror Plasma Confinement," Proc. of the High-Beta Workshop, p 702. ERDA-76/108, Los Alamos, NM July 28 - August 1, 1975).

(16) G.A. Carlson, W.C. Condit, R.S. Devoto, J.N. Doggett, J.D. Hanson, and W.J. Neil, "The Field Reversed Mirror Reactor," Technical Committee Meeting on Fusion Reactor Design, October 10-21, 1977, Madison, WI, to be published, Nucl. Fus. (1978).

(17) L.C. Steinhauer, W. Grossman, and C. Sevier, "The Reversed-Field Multiple Mirror Fusion Concept," 3rd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Santa Fe, NM (May 9-11, 1978).

(18) H.A.B. Bodin, "Study of the Diffusion of High-Beta Plasma in a Theta-Pinch," Phys. Fluids 12, 2171 (1969).

(19) J.P. Freidberg and H. Weitzner, "End Loss from a Linear Theta Pinch," Nucl. Fus., 15, 217 (1975).

(20) J.U. Brackbill, M.T. Menzel, and D.C. Barnes, "Numerical Studies of the Linear Theta Pinch," Proc. 3rd Topical Conf. on Pulsed High-Beta Plasmas, p 375, Culham, England (1976).

(21) K.F. McKenna, and T.M. York, "End Loss from a Collision Dominated Theta Pinch," Phys. Fluids, 20, 9, 1556 (1977).

(22) R.L. Morse, "Adiabatic End Loss from a Theta-Pinch," Phys. Fluids, 11, 1558 (1968).

(23) J.A. Wesson, Proc. 2nd IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Culham, England, 1, 223 (1966).

(24) J.B. Taylor and J.A. Wesson, "End Losses from a Theta Pinch," Nucl. Fus., 5, 159 (1965).

(25) J.P. Freidberg, unpublished, LASL (1975).

(26) J.M. Dawson, A. Hertzberg, R.E. Kidder, G.C. Vlases, H.G. Ahlstrom, and L.C. Steinhauer, "Long Wavelength High Powered Lasers for Controlled Thermonuclear Fusion," Proc. 4th International IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, 1, 673 (1971), Madison, WI.

(27) R.J. [illegible], [illegible] A. [illegible], K.F. McKenna and [illegible], "[illegible] End [illegible] Experiment on [illegible] Pinch," Phys. Rev. Lett., [illegible], 157 ([illegible]).

(28) R.L. Miller and R.A. Krakowski, "Thermal Conduction and Alpha-Particle Constraints for the Ignition of a D-T Linear Magnetic Fusion (LMF) Reactor," submitted to Nucl. Fus., 1978, (also USDOE Rept. LA-UR-78-[illegible] (1978)).

(29) L. Spitzer, Jr., Physics of Fully Ionized Gases, Interscience Publishers, Inc., p. 87 ([illegible]).

(30) R.L. [illegible] and K.F. McKenna, personal communication, LASL (1977).

(31) J.A. Wesson and F.A. Haas, "Stability of the Theta Pinch," Phys. Fluids, 9, 2472 (1966).

(32) F.A. Haas and J.A. Wesson, "Stability of the Theta Pinch II," Phys. Fluids, 10, 2245 (1967).

(33) M.G. Haines, "Plasma Containment in Cusp-Shaped Magnetic Fields," Nucl. Fus., 17, 4, [illegible] (1977).

(34) V.V. Mirnov and D.D. Ryutov, "Gas Dynamic Description of a Plasma in a Corrugated Magnetic Field," Nucl. Fus., 12, 627 (1972).

(35) G.E. Vekstein, D.D. Ryutov, M.D. Spektor, and P.Z. Chebotaev, J. Appl. Mech. and Tech. Phys., 6, 3 (1974 (also LASL Translation LA-TR-75-39 (1975)).

(36) A. Makhijani, A.J. Lichtenberg, M.A. Lieberman, and B.G. Logan, "Plasma Confinement in Multiple Mirror Systems, I, Theory," Phys. Fluids, 17, 1291 (1974).

(37) A.J. Lichtenberg and M.A. Lieberman, "Multiple Mirror Confinement with Collision-Independent Scattering," Nucl. Fus., 16, 532 (1976).

(38) L.C. Steinhauer (ed.), "A Feasibility Study of a Linear Laser Heated Solenoid Fusion Reactor," Electric Power Research Institute Report EPRI-ER-246 (1976).

(39) G.E. Gryczkowski, R.A. Krakowski, L.C. Steinhauer, and J. Zumdieck, "First-Wall Design Limitations for Linear Magnetic Fusion Reactors," 3rd ANS Topical Meeting on the Technology of Controlled Nucl. Fus., Santa Fe, NM (May 9-11, 1978).

(40) R.W. Moses, R.A. Krakowski, and R.L. Miller, "Fast-Imploding-Liner Fusion Power," Proc. 3rd ANS Topical Meeting on Controlled Nuclear Fusion, Santa Fe, NM (May 9-11, 1978).

(41) L. Steinhauer and D. Quimby, "Advances in Laser Solenoid Fusion Reactor Design," ibid.

(42) R.A. Krakowski, F.L. Ribe, T.A. Coultas, and A.J. Hatch, "An Engineering Design of a Reference Theta-Pinch Reactor (RTPR)," USAEC Rept. LA-5336/ANL-8019 (1974).

(43) R.L. Hagenson, R.A. Krakowski, and K.I. Thomassen, "A Toroidal Fusion Reactor Based on the Reversed Field Pinch," IAEA Conf. and Workshop on Fusion Reactor Design, October 10-21, 1977, Madison, WI, to be published in Nucl. Fus. (1978).

(44) R.L. Hagenson and R.A. Krakowski, "A Cost Constrained-Design Point for the Reversed-Field Pinch Reactor (RFPR), 3rd ANS Topical Meeting on the Technology of Controlled Nucl. Fus., Santa Fe, NM (May 9-11, 1978).

(45) R.R. Bartsch, et al., "Plasma Experiments on the Staged Theta Pinch, the Implosion Heating Experiment, and the Scyllac Feedback Experiment," Proc. IAEA Conf. on Plasma Physics and Controlled Fusion Research, III, 381, Berchtesgaden, FRG (1976).

(46) R.A. Krakowski, R.L. Miller and R.L. Hagenson, "Operating Point Considerations for the Reference Theta-Pinch Reactor (RTPR)," Proc. of the 2nd Topical Meeting on the Technol. of Controlled Nucl. Fus., 1, 359, Richland, Washington (September 21-23 1976).

(47) L.C. Steinhauer, "Laser Beam-Plasma Coupling in Laser Solenoid Plasmas," Phys. Fluids 19, 1740 (1976).

(48) R. Massey, K. Berggren, and Z.A. Pietrzyk, "Observation of Stimulated Brillouin Backscattering from an Underdense Plasma," Phys. Rev. Lett., 36, 963 (1976).

(49) A.A. Offenberger, M.R. Cervenan, A.M. Yam, and A.W. Pasternak, "Stimulated Brillouin Scattering of CO_2 Laser Radiation from Underdense Plasma," J. Appl. Phys., 47, 1451 (1976).

(50) T. Dehart, J. Zumdieck, A.L. Hoffman, and D. Lowenthal, "The Laser-Heated Solenoid Proof of Concept Experiment (PCX) Facility," Proc. 7th Symp. on Eng. Problems of Fusion Research, Oak Ridge, Tennessee (October, 1977).

(51) I.W. Johnston and J.M. Dawson, "Correct Value for High-Frequency Power Absorption by Inverse Bremsstrahlung in Plasmas," Phys. Fluids, 16, 722 (1973).

(52) "Summary Plant Description: A Fusion Concept Based on Relativistic-Electron-Beam Heating Solenoid," Physics International Rept. PITR-1156-2 (February, 1978).

(53) L. Thode, "Plasma Heating by Scattered Relativistic Electron Beams: Correlations Among Experiments, Simulation and Theory," Phys. Fluids 19, 831 (1976).

(54) K. Nishikawa, "Parametric Excitation of Coupled Waves I. General Formulation," J. Phys. Soc., Japan, 21, 916, 1152 (1968).

(55) J. Benford, et al., Proc. 7th European Conf. on Plasma Physics and Controlled Thermonuclear Fusion, Lausanne, Switzerland, II, 143 (1975).

(56) B. Bernstein, I. Smith, "AURORA, an Electron Accelerator," IEEE Trans. Nucl. Sci., NS-18, 296 (1971).

(57) A.V. Borodin, et al., "Magnetoacoustic Oscillations and Instability in an Induction Pinch," Soviet Physics JETP 14, 228 (1962).

(58) L. Lindberg and L. Danielsson, "Magneto-acoustic Oscillations in a Cylindrical Plasma Column," Phys. Fluids, 6, 796 (1963).

(59) R. Gerwin, personal communication, LASL (1977), also J.M. Dawson, "Unplugged, Long, Straight Systems for Thermonuclear Reactors," UCLA Rept. PPG 329 (October, 1977).

(60) H.A.B. Bodin, J. McCartan, A.A. Newton, and G.H. Wolf, "Diffusion and Stability of a High Beta Plasma in an 8 Meter Theta Pinch," Proc. IAEA Conf. on Plasma Physics and Controlled Nucl. Fus. Research Novosibirsk, USSR, 2, 533 (1969).

(61) R.S. Thomas, H.W. Harris, F.C. Jahoda, G.A. Sawyer, and R.E. Siemon, "Plasma Experiments on the Linear Scyllac Theta Pinch," Phys. Fluids, 17, 1314 (1974).

(62) R.F. Gribble, W.E. Quinn, and R.E. Siemon, "Plasma Experiments with a Three-Meter Theta-Pinch," Phys. Fluids 14, 2042 (1971).

(63) A. Kadish, "End Shorting Induced Rotation in a Theta Pinch," Phys. Fluids, 19, [illegible] (1976).

(64) N. Amherd, "EPRI Study of Alternative Fusion Reactor Concepts," personal communication (1978).

(65) "Fusion Applications of Fast Discharging Homopolar Machines," Electric Power Research Institute Report EPRI ER-[illegible] (January, 1978).

(66) J. Hammel, personal communication, LASL (1978).

(67) J.G. Linhart, "Very High Density Plasmas for Thermonuclear Fusion," Nucl. Fus., 10, 211 (1970).

(68) N. A. Krakowski, R.L. Hagenson, and R.L. Miller, "Preliminary Scoping Study of [illegible]

(69) [illegible]